The influence of goal-state access cost on planning during problem solving

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Two problem solving experiments investigated the relationship between planning and the cost of accessing goal-state information using the theoretical framework of the soft constraints hypothesis (Gray & Fu, 2004; Gray, Simms, Fu, & Schoelles, 2006). In Experiment 1, thirty-six participants were allocated to Low, Medium and High access cost conditions and completed a problem solving version of the Blocks World Task. Both the nature of planning (memory-based or display-based) and its timing (before or during action) changed with High goal-state access cost (a mouse movement and a 2.5 s delay). In this condition more planning before action was observed, with less planning during action, evidenced by longer first-move latencies, more moves per goal-state inspection and more short (≤0.8 s) and long (>8 s) 'pre-planned' inter-move latencies. Experiment 2 used an eight-puzzle-like transformation task and replicated the effect of goal-state access cost when more complex planning was required, also confirmed by sampled protocol data. Planning before an episode of move making increased with higher goal-state access cost, and planning whilst making moves increased with lower access cost. These novel results are discussed in the context of the soft constraints hypothesis.

INTRODUCTION

Miller, Galanter and Pribram (1960), in their seminal book, discussed how planning was a ubiquitous and intrinsic feature of human behaviour. This paper investigates the nature of planning during problem solving and how this is affected by the cost of accessing information. The theoretical framework for our two studies belongs to Anderson's theory of the Adaptive Character of Thought (1990) and the more recent theory of 'soft constraints' (Gray & Fu, 2004), both of which explain the selection of cognitive strategy as a response to the characteristics of the task environment. We adopt the perspective that planning in problem solving can use and be distributed between internal and external memory (Norman, 1993) and that this balance can be affected by information access cost, defined as the time, physical effort and mental effort required to access information (Gray, Simms, Fu, & Schoelles, 2006). Information access costs represent hard constraints in the soft constraints hypothesis (Gray et al, 2006) and their effects have been investigated with respect to VCR programming (Gray & Fu, 2001; 2004), routine copying (Fu & Gray, 2000; Gray et al, 2006) and exploratory behaviour (Fu & Gray, 2006). The way such costs affect the nature and timing of planning in problem solving has not been researched, and this is the focus of the current paper.

Despite the importance of planning to successful problem solving (Polya, 1957), many studies have found little or no planning ahead during problem solving (e.g., Atwood & Polson, 1976; Delaney, Ericsson & Knowles, 2004). Indeed, it has often been concluded that human problem solvers operate opportunistically and resist planning ahead unless they are encouraged to do so (Hayes-Roth & Hayes-Roth, 1979). One method to achieve this is through instruction. Problem solvers can be induced to plan when given instructions to do so, although the extent of planning is limited by the number of sub-goal chunks that can be encompassed (Ward & Allport, 1997; Phillips, Wynn, McPherson, & Gilhooly, 2001). A second method is to manipulate the task environment such that the costs of not planning outweigh those of planning. One novel means of achieving this, investigated in this paper, is to manipulate the cost of accessing goal-state information in order to induce a more intensive memory-based strategy that will involve more planning before action. First, the theoretical rationale of the soft constraints hypothesis together with the evidence for manipulating this variable in other types of task is discussed, followed, second, by how this would be predicted to affect planning in problem solving.

Manipulating information access cost

Prediction and explanation of the effect of manipulating 'costs' in the task environment stems from Anderson's (1990) theory of the Adaptive Character of Thought (ACT) and, more recently, the theory of soft constraints (Gray & Fu, 2004; Gray et al, 2006). Anderson proposed that human cognition adapts to create optimal solutions to the information processing problems posed by particular task environments (Anderson & Lebiére, 1998). Recent extensions to this perspective have demonstrated that even millisecond changes to the presentation of information can have surprisingly large consequences for the selection of strategies (Gray & Boehm-Davis, 2000), and this has been formalised into the theory of soft constraints (Gray & Fu, 2004). Hard constraints, according to Gray and colleagues, determine behaviour that is or is not possible. Soft constraints, on the other hand, determine what strategy is most likely to be chosen. It is assumed that when selection between strategies is non-deliberate or automatic, soft constraints are determined by tradeoffs in time costs for task performance (Gray et al, 2006).

Fu and Gray (2000) explored this using the Blocks World Task (BWT), the aim of which is to recreate a pattern of coloured blocks. The cost of viewing the target pattern was either holding down a function key, moving a mouse cursor over the target pattern or the latter plus an additional lock-out time of one second per uncovering. As access cost increased, participants used the interface less as an external memory source (O'Regan, 1992) and relied more upon internal memory to complete the task. Evidence for this was that participants in the High-Cost condition accessed the target pattern less frequently and copied more blocks per viewing. When access cost was low, strategy selection minimised the use of internal memory, because the relative costs of encoding and retrieval (memory is assumed to be somewhat volatile) were deemed higher than relying upon the display as an external memory source. This was termed a 'display-based' strategy, by Gray and colleagues. In contrast, when access cost was high, participants chose to commit to memory a number of blocks per target viewing, and subsequently copied each of these blocks from memory before returning to the target pattern to encode another chunk of blocks (Chase & Simon, 1973). This more memory-based strategy avoided much lockout time under High access cost.

These effects of information access cost on the deployment of memory have also been demonstrated using a VCR procedural programming task (Duggan & Payne, 2001; Gray & Fu, 2001; 2004), thus the theoretical basis and empirical effects of manipulating information access cost have been established on copying and procedural tasks. However, to date there is no direct evidence of the effect of information access cost on problem solving, and more specifically, planning. Below we discuss some indirect evidence and also spell out how both the type and nature of planning is expected to vary with manipulation of a specific form of information access cost, namely goal-state access cost. .

The effect of goal-state access cost on planning in problem solving

It can be argued that the reason so little planning ahead has been observed in some problem solving studies (e.g., Atwood & Polson, 1976; Delaney et al., 2004) is that in most studies the goal- and current-states are visible at all times. Consequently, on-line or concurrent planning can take place during problem solving that involves little extra cost and avoids the burden of planning ahead and remembering an initial plan during problem solving. Fu and Gray (2006) found that information-seeking behaviour varied with respect to its utility and cost in their train route exploration task, but effects on planning were not examined. The only other studies we know that have directly manipulated costs of interacting in a problem solving environment were by Pfeiffer (2004) and O'Hara & Payne (1998, 1999). Pfeiffer (2004) manipulated implementation cost and the availability of current-state information (with no effects on planning reported). In a well-cited study, O'Hara & Payne (1998) manipulated move implementation cost and found that problem solvers' propensity to plan ahead during solution of the eight-puzzle was improved by an increase in the implementation cost of making a move. When the cost of making each move was increased from pressing a function key to typing a string, the number of moves to solution reduced significantly. Evidence of increased planfulness came from longer inter-move latencies and verbal protocol analyses. This effect of greater planning was replicated in a further study by O'Hara & Payne (1999) that increased either the time for 'undoing' a move in the slide-jump puzzle (Experiment 1) or the delay in implementing the next move in the eight-puzzle (Experiment 2).

In the following studies, rather than manipulating implementation cost or availability of current-state information, we vary the cost of accessing goal-state information and assess its impact on planning. First, this is practically relevant because modern-day problem solvers have to integrate more and more information from different sources with different access costs (Woods, Patterson & Roth, 2002). Second, we argue that manipulation of access to the goal-state will have a more direct effect on planning and will provide a powerful reminder of the effect of not planning. Indeed planning can only take place when the goal- and current-states are simultaneously available and can be compared, unless the goal-state, or some part of it, is memorised. Therefore, the effect of an access cost imposed on the goal-state is focused on the input side of a problem solving cycle, and more specifically, constrains when the difference between the goal- and current-states can be most easily evaluated, which, in turn informs the planning of subsequent moves. This contrasts with the focus of implementation cost that, as the term suggests, is on the output side of the problem solving cycle and is not so directly targeted at the opportunity for planning that is manipulated by denying constant access to the goal-state. Thus we predict that participants will combat the higher costs of accessing goal-state information by planning ahead and using internal memory in order to avoid the access lockout time and reduce overall task time, as predicted by the soft constraints hypothesis.

It is predicted that planning under high goal-state access cost will occur before a series of problem solving moves, in contrast to planning when there is no access cost that will be more display-based and online (e.g., Larkin, 1989; Payne, 1991). This relates to a recent distinction made by Davies (2003) between ‘initial planning’ and ‘concurrent planning’. Because increased goal-state access cost will lead to greater planning and subsequent reliance on internal memory, one would expect more planning to take place not only initially before any move takes place, but also before a series of moves are executed during problem solving.

It is argued that the costs associated with accessing goal-state information in the realm of one or two seconds will promote episodes/stages of planning throughout problem solving that do not involve move making. On the other hand, when there is little or no goal-state access cost, this will lead to a more display-based interaction with more reliance on external memory and planning whilst making moves. Rather than adopt the term initial planning, we refer to such instances as ‘planning before action’. In contrast, display-based planning performed whilst making moves will be referred to as ‘planning during action’. There are various alternative perspectives to our prediction that increased access cost for goal-state information will result in more memory-based planning before action. First, participants working with a high access cost may choose to memorise the goal-state when accessing it and then return to the current-state to engage in planning during action (without having made a plan when viewing the goal-state). Second, the inability to check the progress of a plan during its execution may lead participants to deem memory-based planning less worthwhile and thus the increased access cost might result in a reduced tendency to plan before action.

Two experiments are reported that examine the effect of goal-state access cost on planning in trying to solve two variations of an eight-puzzle-like transformation task. Experiment 1 used a problem solving task derived from the BWT and Experiment 2 used a more complex version similar to the eight-puzzle (Ericsson, 1975) that required greater planning. In both Experiments, indicators of planning included time taken to make the first move, number of moves made per goal-state viewing, and inter-move latencies. Analysis of these data will provide insight into the timing of planning (before or during action) and the nature of planning (memory-based or display-based).

EXPERIMENT 1

The aim of Experiment 1 was to explore the role of goal-state access cost in affecting the use of planning during solution to the Blocks Problem Solving Task (BPST), derived from the BWT, which is described in the following section. The main hypothesis predicted that as the cost of accessing goal-state information increased, memory-based planning before action will increase and display-based planning during action will decrease.

Method

Participants

Thirty-six Cardiff University Psychology students participated in the study for course credit and were randomly assigned to one of three information access cost conditions.

Apparatus/Materials

The BPST was designed to integrate the surface characteristics of the BWT (Gray et al., 2006) with the task characteristics of the eight-puzzle (Ericsson, 1975). The aim of the BPST, as with the eight-puzzle, was to move blocks in the current-state to match the goal-state (see Figure 1). The task was designed so that cost of accessing the goal-state could be manipulated (see Design section). The current-state remained visible at all times so that participants in all conditions could choose to view both windows simultaneously to support planning behaviour. The cost of doing this was directly affected by the cost of accessing the goal-state. The rules of the BPST were that only one coloured block in the current-state could be moved at a time into an adjacent empty (white) space.

[Insert Figure 1 about here]

The experiment was conducted using a *Tobii 1750* 34 x 27 cm eye-tracker monitor, extended keyboard and mouse. All eye movements were recorded at a rate of 15 frames per second, with time-stamp accuracy of +/-3 ms. When analysing these data, an analysis filter ensured that all fixations larger than 30 pixels and longer than 100 ms in duration were included. Gaze estimation was within 1 degree of accuracy, even across large head movements, and mouse movements and key presses were recorded to log file. The goal- and current-state were the same size, and ten coloured blocks and six empty spaces resided within each 4 x 4 grid. No colours were used twice, and the empty spaces were always white.

Design

Goal-state access cost was manipulated between-subjects in order to negate possible asymmetric transfer (e.g., Poulton, 1982). The current-state was visible at all times in all conditions, but the cost of accessing the goal-state varied according to three conditions. The goal-state was visible at all times in the Low access cost condition. In contrast, the goal-state was covered by a grey mask in Medium or High access cost, and could only be uncovered by placing the mouse cursor over the goal-state. The grey mask then reappeared when the mouse cursor left the goal-state. There was an additional 2.5 s delay associated with uncovering the goal-state when the access cost was High. Different goal- and current-states were used for each of the twelve experimental trials and blocks were moved in the current-state by selecting the block to move via a left mouse click and pressing the corresponding arrow key on the keyboard.

All dependent measures were saved to log file at a temporal resolution of 15.63 ms. The time taken to make the first move was an indication of initial planning time before any action was taken. The average number of moves made per inspection of the goal-state was an indication of planning using internal memory. In accordance with Gray & Fu (2001; 2004), data from the Medium and High goal-state access cost conditions were derived from the number of moves in the current-state per uncovering of the goal-state. Necessarily, the eye-tracker was used to derive these data from the Low access cost condition (with consecutive fixations in the goal-state being collapsed and counted as one). The eye-tracker also measured the number of eye fixations made between the goal- and current-state during periods when participants in the Medium and High access cost conditions chose to cease making moves and view both simultaneously. More glances between the goal- and current-state are likely to reflect more comparative evaluation and planning. All inter-move latencies were also collected because they provide insight into planning behaviour (Ericsson, 1974; O'Hara & Payne, 1998), with longer latencies tending to be associated with the first move after a long period of planning and very short inter-move latencies being indicative of the 2nd, 3rd, etc moves that are simply and quickly executed as they are pre-planned. Medium-sized latencies are more likely to reflect planning whilst moving, and these would be more along the lines of make-one-move, plan-next-move, make-one-move, plan-next-move. This interpretation is consistent with Ericsson (1974), who highlighted $\leq$ 0.8 s and >8 s inter-move latency categories as representative of complex planning. The former category is indicative of a fixed process of making a pre-planned move. The latter is indicative of planning *before* a series a moves. In contrast, inter-move latencies >0.8 s and ≤8 s in duration are likely to represent various forms of planning *during* action, and this category may be more heterogeneous (cf. Ericsson, 1974). Finally, the number of moves and the time taken to complete each problem was recorded, indicative of problem solving proficiency. Error data were recorded, but are not reported because of extremely low frequencies unaffected by goal-state access cost.

Procedure

Participants were seated approximately 50 cm away from the eye-tracker and two practice trials followed successful eye-tracker calibration (16-point). Each participant within each of the three access cost conditions then received a different randomised order of experimental trials. When participants were satisfied they had solved a problem they clicked a button labelled "stop trial". The next trial then began if the goal-state had been correctly achieved, otherwise they were required to continue until solved.

Results & Discussion

As the cost of accessing the goal-state increased, it was predicted that planning before action would increase and this would result in longer first-move latencies, more moves per goal-state viewing, more eye fixations between the goal- and current-state when both windows were open in the Medium and High access cost conditions, and more inter-move latencies ≤.08 s and >8s in duration. The latency preceding the first move on each trial is an indicator of initial planning time (Davies, 2003), and log transformed first-move latencies differed significantly as a function of goal-state access cost (see Table 1), F (2, 33) = 29.16, MSE = 0.25, p <.001. Post hoc analyses revealed significant differences between all access cost conditions (*ps* <.05), and the only effect of excluding the movement times and access delays incurred during the Medium and High conditions, F (2, 33) = 15.16, MSE = 0.30, p <.001, was the loss of the significant post hoc difference between the Medium and High conditions (see Appendix A for exclusion data of movement times and access delays). However, both first-move latency means of the Medium and High access cost conditions fall into Ericsson's >8 s category and indicate planning of a series of moves before action. First-move latencies were also affected by practice, F (7.01, 231.16) = 4.06, MSE = 0.04, p <.001, but there was no access cost x practice interaction (where violations of sphericity occurred, Greenhouse-Geisser corrected degrees of freedom are reported accordingly).

[Insert Table 1 about here]

There was a dramatic increase in the average number of moves each participant made per goal-state inspection as access cost increased (see Table 1), also suggesting more planning before action with higher goal-state access costs, F (2, 33) = 90.78, MSE = 0.03, p <.001. Post hoc analyses revealed significant differences between all access cost conditions (*ps* <.001). Because the eye-tracker was not set up to break data down by trial in Experiment 1, analysis of the effect of practice could only be computed for Medium and High access cost conditions. A separate 2 (access cost Medium/High) x 12 (trial) ANOVA again found an effect of access cost and also found a significant effect of practice, F (4.64, 102.12) = 3.13, MSE = 0.01, p <.001, with the number of moves made per goal-state inspection increasing with practice (First Problem: *Mean* = 5.46, *SD* = 3.34; Final Problem: *Mean* = 7.89, *SD* = 6.02). This may suggest the development of an encoding schema for goal-state information as a function of practice (at least in the Medium and High access cost conditions). There was, however, no access cost x practice interaction.

The effect of access cost on the number of eye fixations between the goal- and current-state per uncovering of the goal-state (i.e. when both the goal- and the current-state were visible), F (1, 22) = 25.45, MSE = 2.17, p <.001, also indicated that participants viewed both windows simultaneously more often in the High than Medium access cost condition (see Table 1), suggesting that more evaluation and comparative planning took place when there was a higher cost associated with accessing the goal-state.

[Insert Figure 2 about here]

In order to investigate the effect of goal-state access cost on inter-move latencies during all problem solving, a 3 (access cost Low/Medium/High) x 3 (category Short/Intermediate/Long) x 12 (practice) ANOVA with the first factor manipulated between-subjects and the other factors manipulated within-subjects was computed on log transformed frequency data. A significant interaction between access cost and category was observed, F (3.18, 52.510) = 49.93, MSE = 0.02, p <.001, and simple main effects indicated that the effect of access cost was significant at each of the three categories (*ps* <.001). A significantly higher number of latencies in the shortest (≤0.8 s) and longest categories (>8 s) came from the High than Low access cost condition, supporting the assertion that higher access costs would promote more planning before action (*ps* <.05). In addition, the intermediate inter-move latency category (>0.8, ≤0.8 s) was found to contain significantly more latencies from the Low than High access cost condition (*p* <.001), suggesting that planning during action was more commonplace in the Low access cost condition. A practice x category interaction was also observed, *F* (111.32, 373.60) = 4.48, *MSE* = 0.02, *p* <.001, and simple main effects indicated that practice had a significant effect in all but the <.08 s category. (Note that the above analyses of inter-move latencies included movement times and access delays in the Medium and High access cost conditions. However, these results were not affected by the exclusion of these data. The information access cost x category interaction was, *F* (2.92, 48.12) = 24.11, *MSE* = 0.03, *p* <.001, and subsequent post hocs were unaffected.)

Of subsidiary interest was the effect of goal-state access cost on problem solving proficiency in terms of solution time and number of moves (see Table 1), although no predictions were made concerning these measures. Solution times were affected by access cost when all movement times and delays were included, *F* (2, 33) = 9.69, *MSE* = 185.60, *p* <.001, with post-hoc analyses revealing longer times in the High than both the Low and Medium information access cost conditions, *p* <.001. However, this effect disappeared when movement times and delays incurred in the Medium and High access cost conditions were excluded, *F* (2, 33) = 2.97, *MSE* = 2022.03, *p* >.05. Moves-to-solution data were not affected by access cost, *F* (2, 33) = 0.02, *MSE* = 153.38, *p* >.05, but with practice participants in all conditions were able to reduce task completion times (First Problem: *Mean* = 83.70 s, *SD* = 26.61; Final Problem: *Mean* = 63.39 s, *SD* = 18.83), *F* (11, 363) = 6.33, *MSE* = 0.01, *p* <.001, and moves-to-solution (First Problem: *Mean* = 43.54, *SD* = 10.28; Final Problem: *Mean* = 41.72, *SD* = 10.41), *F* (7.11, 234.58) = 2.06, *MSE* = 258.53, *p* <.05.

In summary, Experiment 1 has provided evidence that small changes to the cost of accessing goal-state information do affect the nature of planning, including its timing and the selection between memory-based and display-based strategies during problem solving. Rather than simply memorising the goal-state and subsequently planning during action when in the current-state, participants in the High access cost condition chose to make plans ahead of action (when viewing both the goal-state and current-state simultaneously) and executed these pre-planned moves quickly when in the current-state. There is also no evidence that the inability in the Medium or High access cost conditions to check the progress of a plan during its execution reduced planning before action. Although performance improved over time, these changes in planning style were largely unaffected by practice. Not only was there more initial planning under high access cost, but more planning took place whenever the goal-state was accessed in this condition, as indicated by the increase in the number of moves per goal-state viewing. This interpretation is corroborated by more eye fixations between the goal- and current-state in the High than Medium access cost condition when the goal-state was visible. Interestingly the increased planning before action with its attendant internal memory cost had no effect on problem solving proficiency. One might have expected moves-to-solution to increase with more planning before action, although one interpretation is that extra memory/planning errors made when access costs were High were equivalent to the extra moves required by the more piecemeal trial and error approach adopted by the Low and to a lesser extent by the Medium access cost condition.

Experiment 2 was designed to attempt to replicate these findings using a problem solving task that involved more complex planning. In addition, supplementary evidence from sampled concurrent verbal protocols was collected to further corroborate the effect of goal-state access cost on planning during problem solving.

EXPERIMENT 2

In order to evaluate whether the results from Experiment 1 generalised to a problem solving task requiring more complex planning, the BPST used in Experiment 1 was modified to mimic more closely the problem solving demands of the much researched eight-puzzle (see Ericsson, 1975; O'Hara & Payne, 1998). Because there are only eight tiles and one empty space, complex planning is crucial to solution of this task (Pizlo & Li, 2005).

Some concurrent verbal protocol data were collected to supplement the measures used in Experiment 1 and to further test the hypothesis that higher goal-state access costs promote more planning before action and discourage display-based planning during action. Although some discussion has arisen over the years regarding the potential impact of verbal protocol methodology upon task performance (e.g., Schooler, Ohlsson, & Brooks, 1993), converging evidence now suggests that verbal protocol does not affect the nature of processing, provided that only items naturally attended to by participants are verbalised (Brinkman, 1993; Fleck & Weisberg, 2004; Newell & Simon, 1972). Protocols in the current paper were collected concurrently to avoid memory biases associated with retrospective methods (van Gog, Paas, van Merriënboer, & Witte, 2005) and analyses of verbal protocol data were situated in the context of eye-tracker and other action data (Patrick & James, 2004).

Although the use of verbal protocol in the current context will require some innovation, Ericsson (1975) provided a useful framework for the analysis of such data collected during solution to the eight-puzzle and our focus will be on verbalisations that meet his criteria for planning and intention setting (see Appendix B). Following from Davies (2003), planning before action will be characterised by plans verbalised whilst no moves were made, whereas planning during action will be characterised by plans verbalised whilst a minimum of one block was being moved. It was predicted that as goal-state access cost increased there would be a shift away from verbalisations of planning during action to those concerning planning before action.

Method

Participants

Thirty-six Cardiff University Psychology students participated in the study for course credit and were randomly assigned to one of three information access cost conditions.

Apparatus/Materials

In addition to the experimental and recording equipment used in Experiment 1, a wireless microphone was used to record concurrent verbal protocol. The number of blocks contained in each window was reduced from sixteen to nine, eight of the blocks were coloured differently and one was empty (white).

Design

The experimental design was identical to that of Experiment 1, but participants were required to complete six eight-puzzle-like BPST problems within a sixty minute time-limit. The eye-tracker was also set up to allow the segmentation of eye fixation data by trial.

Procedure

We asked participants to think aloud as they were problem solving. To facilitate this they were given instructions and practice exercises involving different tasks and contexts (as recommended by Ericsson & Simon, 1993). If participants were silent for a period of fifteen seconds during problem solving they were prompted with the non-directive prompts; “What are you thinking?” and “Please keep talking”. Participants were required to complete a short practice task that required the movement of each block in a sequence. This allowed participants to familiarise themselves with the method of moving blocks and accessing the goal-state (dependent upon information access cost) whilst thinking aloud. Different block configurations were used for each problem, and every participant within each access cost condition received one of twelve different randomised problem orders.

Verbal protocols were collected, transcribed and segregated into semantically related segments. Each segment was independently coded by two persons using five categories derived from Ericsson (1975), although only the data relating to the planning and intention setting categories are reported in the main results. Verbal protocol data were combined with eyetracker data to ensure that episodes of verbalisation categorised as planning during action were indeed referring to the moves being made at that time.

Results & Discussion

The effect of goal-state access cost on measures of planning are described first, followed by the sampled verbal protocol analyses.

Effect of goal-state access cost on planning

In line with Experiment 1, initial planning increased in conjunction with goal-state access cost (see Table 2), F (2, 33) = 16.32, MSE = 0.14, p <.001, with post hoc analyses revealing longer first-move latencies in the High access cost condition than the Low (p <.001). The first-move latency means of all access cost conditions fall into Ericsson's >8 s category and indicate planning of a series of moves before action, but initial planning was not affected by practice, F (3.00, 98.87) = 0.58, MSE = 211.54, p >.05. (Note that this result was derived from data including movement times and access delays in the Medium and High access cost conditions. However, the result is not affected by the exclusion of these data. The main effect of goal-state access cost becomes, F (2, 33) = 9.75, MSE = 0.15, p <.001, and subsequent post hocs are unaffected.)

[Insert Table 2 about here]

There was an increase in moves per goal-state inspection as goal-state access cost increased (see Table 2), also indicating more planning before action throughout problem solving, F (2, 33) = 66.78, MSE = 0.01, p <.001. As with Experiment 1, participants responded to an increase in access cost by making more moves per goal-state inspection, and post hoc analyses revealed differences between each of the access cost conditions (ps <.001). The number of moves made per goal-state inspection (including data from all conditions) increased with practice (First Problem: *Mean* = 2.84, SD = 2.71; Final Problem: *Mean* = 4.04, SD = 4.07), F (3.66, 120.62) = 10.84, MSE = 0.01, p <.001, suggesting the development of an encoding schema for goal-state information as a function of practice. There was no access cost x practice interaction.

The number of eye fixations between the goal- and current-state per uncovering of the goal-state (i.e. when both the goal- and the current-state were visible) increased with access cost, F (1, 22) = 26.63, MSE = 5.12, p <.001, suggesting more planning as the cost of accessing the goal-state increased from Medium to High. The fact that the values reported here are higher than those observed in Experiment 1 probably reflects an increase in the complexity of planning required to complete this task, which may also be why some learning occurred in the number of moves made per goal-state viewing.

The log transformed inter-move latency data for all trials were analysed. The same inter-move latency categories from Experiment 1 were used, and an interaction between goal-state access cost and category was again observed, F (2.43, 40.04) = 3.96, MSE = 1.03, p <.05, (see Figure 3). Planned comparisons found more short inter-move latencies (≤0.8 s) and more long inter-move latencies (>8 s) came from the High than the Low access cost condition (p <.05 and p <.001 respectively). More inter-move latencies were also found to come from the Low than the High access cost condition in the intermediate category (>0.8 ≤8 s) (p <.01). A practice x category interaction was also found, F (5.85, 193.19) = 20.15, MSE = 0.04, p <.001, with simple main effects indicating that there was a significant effect of practice in all but the <.08 s category. (Note that these results were based on data including movement times and access delays from the Medium and High access cost conditions. However, these results are unaffected by exclusion of these data. The information access cost x category interaction becomes, F (2.47, 40.67) = 3.46, MSE = 0.04, p <.05, and subsequent post hocs were unaffected.)

[Insert Figure 4 about here]

Both measures of problem solving proficiency (moves- and time-to-solution) required log transformations and neither were affected by goal-state access cost (time-to-solution: F (2, 33) = 1.83, MSE = 0.18, p >.05, moves-to-solution: F (2, 33) = 0.20, MSE = 8880.95, p >.05). Although post hoc analyses of time-to-solution data in Experiment 1 revealed significant differences between access cost conditions when movement time and access delays were included, these results were not replicated in Experiment 2 and the exclusion of movement times and access delays from the Medium and High conditions had no effect, F (2, 33) = 1.21, MSE = 0.20, p >.05. However, consistent with Experiment 1, practice reduced both the time (First Problem: *Mean* = 540.38 s, *SD* = 150.15; Final Problem: *Mean* = 259.69 s, *SD* = 116.07), F (5, 165) = 11.19, MSE = 0.08, p <.001, and number of moves required to solve each problem (First Problem: *Mean* = 129.06 s, *SD* = 106.48; Final Problem: *Mean* = 84.56 s, *SD* = 60.22), F (3.66, 120.82) = 2.96, MSE = 7764.18, p <.05. There was no access cost x practice interaction.

The data summarised above replicated the effects of goal-state access cost found in Experiment 1 with a problem solving task requiring more complex planning. There was not only more initial planning under high access cost, but more planning took place whenever the goal-state was accessed in this condition (as indicated by the increase in the number of moves per goal-state inspection). This is also consistent with more eye fixations between the goal- and current-state in High goal-state access cost. Analyses of the distribution of inter-move latencies again suggested that higher access costs prompted more planning before action and less planning during action. Again, the effect of higher access costs promoting more planning that relied on internal memory came at no significant detriment to problem solving proficiency.

Verbal protocol analyses

Some participants verbalised little, and there were also some recording failures. An independent judge blind to the hypotheses selected six participants who verbalised satisfactorily from each of the three access cost conditions and protocols taken during solution to the first and final trial were transcribed and analysed. Any changes in planning with practice would be most evident between these two trials, (c.f. Davies, 2003). The inter-rater reliability was found to be very high, Kappa = 0.92, p <.001, (Cohen, 1960) and the two coders discussed discrepant categorisations and subsequently came to an agreement concerning each. A series of 3 access cost Low/Medium/High) x 2 (problem First/Final) ANOVAs were carried out on the log transformed frequency data for categories of verbalisation closely associated with planning, namely planning before and during action, and intentions before and during action (see Table 3).

[Insert Table 3 about here]

Planning before and during action. As hypothesised, the cost of accessing the goal-state significantly affected the frequency with which plans were verbalised before action, F (2, 15) = 7.94, MSE = 0.84, p <.01, with post hoc analyses revealing significantly more planning before action in the High than the Low access cost condition (p <.05). (There was no effect of practice, nor was there any interaction between access cost and practice for this measure.) Access cost also affected the frequency with which plans were verbalised during action, F (2, 15) = 4.55, MSE = 1.18, p <.05, and as predicted post hoc analyses revealed planning during action to be more frequent in the Low access cost condition than the High (p <.05). (Again, no effect of practice was observed, nor was an interaction found between goal-state access cost and practice.)

Intentions before and during action. The cost of accessing the goal-state significantly affected the frequency with which intentions were verbalised before action, F (2, 15) = 4.29, MSE = 0.93, p <.05, with post hoc analyses revealing significantly more intention setting before action in the High than the Low access cost condition (p <.05). In addition, intention setting before action was significantly more prevalent during solution to the first (*Mean* = 4.39, *SD* = 2.66) than the final problem (*Mean* = 2.56, *SD* = 1.62), F (1, 15) = 7.36, MSE = 0.54, p <.05, but there was no interaction between access cost and practice. Goal-state access cost also affected the frequency with which intentions were verbalised during action, F (2, 15) = 6.50, MSE = 1.15, p <.01, and as predicted, post hoc analyses revealed intention setting during action to be more frequent in the Low access cost condition than the High (p <.05). No effect of practice was observed, nor was an interaction found between goal-state access cost and practice.

Protocol examples. Two excerpts of protocol, one from a Low and one from a High access cost participant, were selected to illustrate representative differences between these two conditions.

Typically, the participant working with a Low access cost (Table 4) began to move blocks without having first instantiated a plan or intention. The solution process then quickly began to encompass verbalisations characteristic of intention setting and planning during action interleaved with regular action evaluations. In particular, the action evaluations illustrated in Table 4 appear typical of opportunistic planning (Hayes-Roth & Hayes-Roth, 1979), in the sense that a particular action was often stopped upon the realisation that it was not going to achieve the desired outcome. The predominance of display-based planning and intention setting during (rather than before) action, coupled with regular action evaluations, represents typical problem solving in the Low access cost condition. In total, this participant recorded one episode of planning before action, six counts of planning during action, five intentions formed before action and fourteen intentions formed during action. In addition, three perceptual descriptions, fifteen action evaluations and fourteen move descriptions were recorded.

[Insert Table 4 about here]

In contrast, the High access cost protocol (Table 5) included the formulation of an intention prior to making any moves. The corresponding moves were then made and subsequently evaluated with regard to the prior intention. The participant then repeated this pattern of problem solving several times, and this extract provides an example of what is meant by ‘episodes’ of planning before action. In total, this participant went on to record six episodes of planning before action, no instances of planning during action, four intentions made before action and one intention made during action. In addition, one perceptual description was recorded, along with ten action evaluations and sixteen move descriptions.

[Insert Table 5 about here]

Analysis of the verbal protocols provide further corroborating evidence of the effect of goal-state access cost on planning during problem solving. Problem solving behaviour with a High access cost associated with accessing the goal-state was characterised by more planning before action, whereas problem solving with a Low information access cost was characterised by more planning during action.

GENERAL DISCUSSION

The aim of this paper was to investigate the relationship between planning and problem solving as a function of the cost of accessing goal-state information, conceptualised within the theoretical frameworks of adaptive cognition (Anderson, 1990; Anderson & Lebiére, 1998) and more recently 'soft constraints' (Gray & Fu, 2004). Two experiments examined how what appear to be small changes to the cost of accessing goal-state information affected planning behaviour during problem solving. As predicted, and despite variations in the nature and complexity of planning between the two transformation tasks, higher access costs were found to encourage greater use of planning before action (Davies, 2003). Lower access costs, on the other hand, were found to promote more reliance upon display-based planning during action. Episodes of planning before action were found to occur not just at the outset of problem solving, which Davies (2003) labeled initial planning, but throughout the problem solving process. Other than the negative effect of goal-state access cost on time-to-solution in Experiment 1 (which disappeared when movement times and access delays from the medium and high information cost conditions had been removed), the manipulation of access cost in this paper had little or no effect on problem solving proficiency. Goal-state access cost had no effect on time-to-solution in Experiment 2, perhaps suggesting that higher access costs have a less negative effect on overall problem solving proficiency when more complex planning is required by the task space.

These novel results shed light on how human problem solvers plan ahead given different task constraints and add substance to our earlier suggestion that classic studies in problem solving (e.g. Atwood & Polson, 1976) need to take account of the importance of the task environment. Seemingly superficial features such as the time to access task-relevant information can influence not only when and how plans are executed, but also the type of plan formed and even the decision whether to plan at all. This observation is not merely a theoretical nicety, because in order to generalise the findings from laboratory based tasks we need to acknowledge and understand the complex interactions between the task environment and the underlying cognitive processes. Our results indicate that these interactions can be affected by changes to information access cost which are commonplace in many everyday and industrial tasks (e.g., word processing - O'Hara, Taylor, Newman, & Sellen, 2002; and process control – Vicente, Moray, Lee, Rasmussen, Jones, Brock, & Djemil, 1996).

This observation is of increasing relevance given the proliferation of information sources due to a variety of technologies (Woods et al., 2002). For example, operators within supervisory environments must form complex plans from an ever increasing array of information (Riley, Endsley, Bolstad & Cuevas, 2006). Our experiments suggest that alterations to the cost of accessing goal-state information could induce different types of planning. Whether encouragement to plan before or during action is desirable depends upon the criteria of task performance. Planning before action may not benefit efficiency of performance in some situations (Phillips et al., 2001), although it will probably result in better memory for previous moves (Delaney et al., 2004) and retrospective planning can enable previous unsuccessful problem states to be avoided (Davies, 2000). More generally, our findings qualify the common assumption within cognitive engineering that displays should seek to minimise cognitive workload by immediately presenting all information required by the user (see Wickens & Hollands, 2000, Wilson, 2002).

A number of limitations of the present studies do, however, need to be addressed. First, goal-state access cost is a heterogeneous variable with contributions from not only time but also physical effort and mental effort that were not separated in these studies. Gray et al (2006) have attempted to delineate among these components of information access cost, and in doing so have concluded that time is the overriding factor. Although not explicitly stated, time also featured as an underlying assumption within O'Hara & Payne's (1998) cost-benefit analysis of implementation cost. Second, our studies make extensive use of eye-tracking data to make inferences regarding the use of internal and external memory. Whilst eye-tracking data can reveal what an individual is looking at, it cannot provide a measure of the degree that fixated information is perceived or processed. Indeed, Anderson, Bothell & Douglass (2004) have argued that conclusive inferences cannot be made from eye-tracking data with respect to retrieval processes, and the extent to which eye fixations are an index of attention is currently under debate (see Horowitz, Fencsik, Fine, Yurgenson, & Wolfe, 2007). Notwithstanding these caveats, we would argue that every measure has its limitations, and the only remedy is to avoid common method error by using multiple methods and measures. Consequently the present study utilised a range of performance measures, supplemented by eye tracking and sampled verbal protocol data, and our identification of different strategies was a result of converging indications from all of these measures.

In conclusion, our studies have demonstrated for the first time that one or two second changes to the accessibility of goal-state information can induce major changes in problem solving strategy in terms of the nature and timing of planning.

This effect is consistent with findings by O'Hara & Payne (1998, 1999) that increasing the cost of implementing an action leads to greater planning in problem solving. However, we have argued that associating a time cost with viewing the goal-state constrains when the goal- and current-states can be compared. This more directly affects the opportunity and need to plan than implementation cost, which is action-oriented and focused more on the output rather than the input side of the problem solving cycle. The encouragement of a more memory-based problem solving strategy, as in the present study, can be advantageous in exploratory learning (Sweller, 1988; Sweller and Levine, 1982) and is essential for effective transfer between different variations of the same task (Vollmeyer, Burns, & Holyoak, 1996). This corresponds with the finding that higher access costs can improve memory for visual-spatial information during interactive behaviour (Waldron, Patrick, Morgan, & King, 2007; Waldron, Patrick, Duggan, Banbury, & Howes, 2008). Indeed, goal-state access costs might pose 'desirable difficulties' where more mental planning leads to better learning in the long run (Schmidt & Bjork, 1992).

Our findings reinforce the importance of taking into account the adaptive view of human cognition (Anderson, 1990; Anderson & Lebiére, 1998) and the 'soft constraints' perspective (Gray & Fu, 2004) when analysing human problem solving and planning behaviour. Further work should examine the robustness of this effect of goal-state access cost on a greater range problem solving tasks and whether and how such access costs can be manipulated, including intermittently, to not only encourage a particular form of planning, but also learning an efficient and generalisable problem solving strategy.

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Appendix A: The method for calculating movement time

Mouse movement times between the goal- and current-state were calculated using a variation of Fitt's law (MacKenzie, 1992). This is a universally accepted approximation of human movement in human-computer interaction and was also used by Gray et al. (2006) in calculating movement time for the BWT. The Fitt's law equation used was $MT = a + b \log_2(A/W + 1)$, where *MT* is movement time, *A* is amplitude (or movement distance) and *W* is the tolerance or width of the target area. We used the ACT-R parameters for Fitt's law (a = 0.05; b = 0.10) derived by Card, English and Burr (1978) that are widely accepted as providing a good fit to moving a mouse cursor, and also used by Gray et al. (2006). The estimated time to make a mouse movement between the goal- and current-state in either direction was 182 ms.

Appendix B: Verbalisation category scheme

Planning before/during action. Verbal statements categorised as plans contained specific information about how the participant was going to attain the desired goal-state or property. Words such as "if", "when" and "then" were useful indicators of verbal statements corresponding to planning activity. If plan development and evaluation were performed whilst not making any moves, then the plan was coded as planning before action. If plan development and evaluation were performed whilst making a minimum of one move, then the plan was coded as planning during action.

Intentions before/during action. Segments of protocol categorised as intentions suggested that the participant was trying to attain a particular goal or property, but did not provide specific indication of how these were to be achieved. For example, "I need to get the green into the correct position". If this intention was verbalised during a period of no moves it was coded as intention before action, whereas if it was verbalised whilst making a minimum of one move, it was coded as intention during action.

Table 1

The Effect of Goal-State Access Cost on Problem Solving (Experiment 1).

Measure	Low Access Cost		Medium Access Cost		High Access Cost	
	Mean	SD	Mean	SD	Mean	SD
First-move latency (s)[1]	5.40	4.20	11.48	7.81	15.97	8.96
First-move latency (s)[2]	5.40	4.20	10.93	7.70	12.89	8.80
Moves per Goal-State inspection	1.12	0.28	3.31	0.83	9.52	3.17
Fixations between goal- and current-state per goal-state uncovering	N/A	N/A	2.09	0.66	5.12	1.97
Time-to-solution (s)[1]	64.03	10.93	63.74	12.02	85.09	17.11
Time-to-solution (s)[2]	64.03	10.93	58.89	20.24	71.72	25.41
Moves-to-solution	41.90	6.14	41.92	4.51	41.19	3.92

[1] Times include movement times and lockout delays incurred in the Medium and High access cost conditions.

[2] Times exclude movement times and lockout delays incurred in the Medium and High access cost conditions.

Table 2

The Effect of Goal-State Access Cost on Problem Solving (Experiment 2).

Measure	Low Access Cost		Medium Access Cost		High Access Cost	
	Mean	SD	Mean	SD	Mean	SD
First-move latency (s)[1]	11.72	7.28	19.75	11.90	26.78	17.57
First-move latency (s)[2]	11.72	7.28	19.00	11.76	23.31	17.34
Moves per Goal-State inspection	1.43	0.60	2.78	1.27	8.03	3.65
Fixations between goal- and current-state per goal-state uncovering	N/A	N/A	3.41	1.43	8.17	2.86
Time-to-solution (s)[1]	305.23	135.89	370.33	136.79	332.41	111.86
Time-to-solution (s)[2]	305.23	135.89	352.66	290.44	295.17	235.42
Moves-to-solution	92.81	29.01	107.92	36.30	100.47	46.16

[1] Times include movement times and lockout delays incurred in the Medium and High access cost conditions.

[2] Times exclude movement times and lockout delays incurred in the Medium and High access cost conditions.

Table 3

The Effect of Goal-State Access Cost on the Frequency of Types of Verbalisation (Experiment 2).

Measure	Low Access Cost		Medium Access Cost		High Access Cost	
	Mean	SD	Mean	SD	Mean	SD
Planning before action	0.17	0.39	1.42	1.16	2.42	3.15
	(0.34)	(0.81)	(6.46)	(5.28)	(13.55)	(9.71)
Planning during action	3.08	2.31	1.67	1.56	0.75	1.06
	(12.86)	(9.98)	(7.38)	(8.12)	(4.43)	(7.70)
Intention before action	2.25	2.34	4.25	2.75	3.75	1.42
	(8.06)	(7.04)	(19.90)	(8.27)	(28.87)	(9.81)
Intention during action	4.92	3.68	3.92	3.96	1.17	0.94
	(18.98)	(9.74)	(14.61)	(11.45)	(10.15)	(11.00)

Note. Values represent mean frequency per trial (with percentage data provided in parentheses).

Table 4

An Extract from a Low Goal-State Access Cost Verbal Protocol (Experiment 2).

Time (s)	Statement	Moves	Fixation	Category
0.00-0.25	Right then, so erm, right, it's messy.	0	Both	Performance evaluation
0.27-0.44	If I bring the red one down, and then I need to get, if I get the green out the way, get the yellow one up.	3	Both	Move description
0.45-0.48	Erm, then get the green into its space.	2	Current-State	Intention during action
0.50-0.55	Ah, oh that's not going to work.	0	Both	Action evaluation
1.00-1.03	move the green one back and move the red one	2	Both	Move description
1.06-1.08	Try and get the red one in its space.	1	Current-State	Intention during action
1.09-1.26	Start with the red one. Then if I move the green one down into its space, and if I try and get the pink one, ah, er, into its space as well.	3	Both	Planning during action
1.29-1.30	Erm, brown.	1	Current-State	Move description
1.33-1.35	And then the blue one's going too far, er.	0	Current-State	Action evaluation
1.40-1.43	I need to swap the blue and the yellow.	0	Both	Intention before action
1.44-1.48	Erm, problem, ah.	0	Both	Action evaluation
1.57-2.03	Erm, ok having a blank, erm.	0	Both	Other
2.03-2.15	Ok, so I need to get the yellow one down and put that one next to the brown one.	5	Both	Intention during action
2.18-2.21	Erm, and then try and get the red one down as well.	2	Current-State	Intention during action
2.26-2.37	Right, erm, right, erm, problem.	2	Both	Action evaluation
2.38-2.42	Yellow one, right lets try another one	0	Both	Intention before action
2.43-2.45	So brown's in the right place, purple is in the right place.	0	Both	Perceptual description
2.45-2.56	Get the pink, erm, get the pink in the right place.	2	Both	Intention during action
3.00-3.04	Right, that's not going to work either.	0	Current-State	Action evaluation

Table 5

An Extract from a High Goal-State Access Cost Verbal Protocol (Experiment 2).

Time (s)	Semantically-related Statement	Moves	Fixation	Category
0.00-0.29	So, I'm going to move the black across, the brown down and the yellow across to start off with.	0	Both	Intention before action
0.35-0.54	Hang on a second, oh this is so confusing. Ok so I'm going to get, ok, ok, brown, I'll get brown into the top corner.	0	Both	Intention before action
0.54-1.02	Brown goes up, green across, yellow down, brown across.	4	Current-State	Move description
1.05-1.07	That's got that in the right place.	0	Both	Action evaluation
1.07-1.17	Now I need to get the yellow and the green out of there, so I'm going to move the yellow.	0	Both	Planning before action
1.18-1.31	Green up, yellow across, black up, purple right, blue right, pink down, red down, green across, yellow up.	9	Current-State	Move description
1.32-1.41	Is that the right way round? That's why, the bottom is messed up.	0	Both	Action evaluation
1.41-1.49	Need to get the pink to the other side, move the whole middle ones around.	0	Both	Planning before action
1.50-1.59	Black across, purple up, blue across, pink across, down black, across, purple across again.	7	Current-State	Move description
2.00-2.02	So pink's in the right place now.	1	Current-State	Action evaluation

Figure captions

Figure 1: An example of a Blocks Problem Solving Task start-state in the low goal-state access cost condition.

Goal-State Window is left, Current-State Window is right.

Figure 2: The distribution of inter-move latencies as a function of goal-state Access Cost (Experiment 1).

Note. Times include IAC and movement delays and error bars represent ± 1 standard error.

Figure 3: The distribution of inter-move latencies as a function of goal-state Access Cost (Experiment 2).

Note. Times include IAC and movement delays and error bars represent ± 1 standard error.

Figure 1

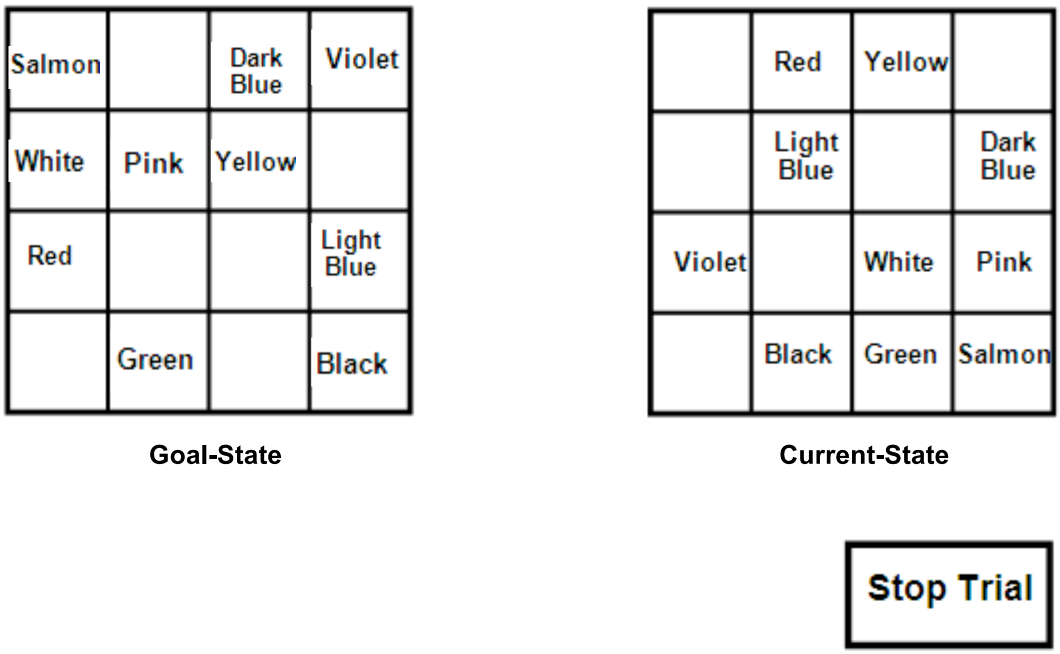

Salmon
Dark Blue
Violet
White
Pink
Yellow
Red
Light Blue
Green
Black
Goal-State
Red
Yellow
Light Blue
Dark Blue
Violet
White
Pink
Black
Green
Salmon
Current-State
Stop Trial

Figure 2

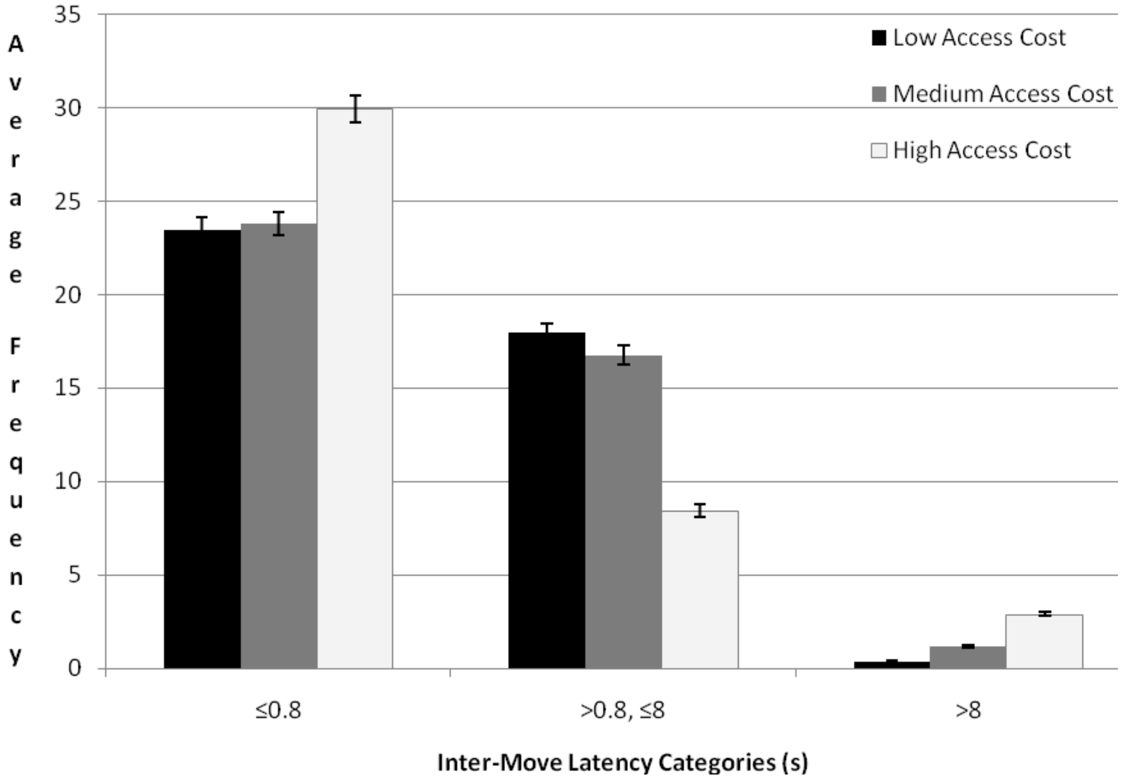
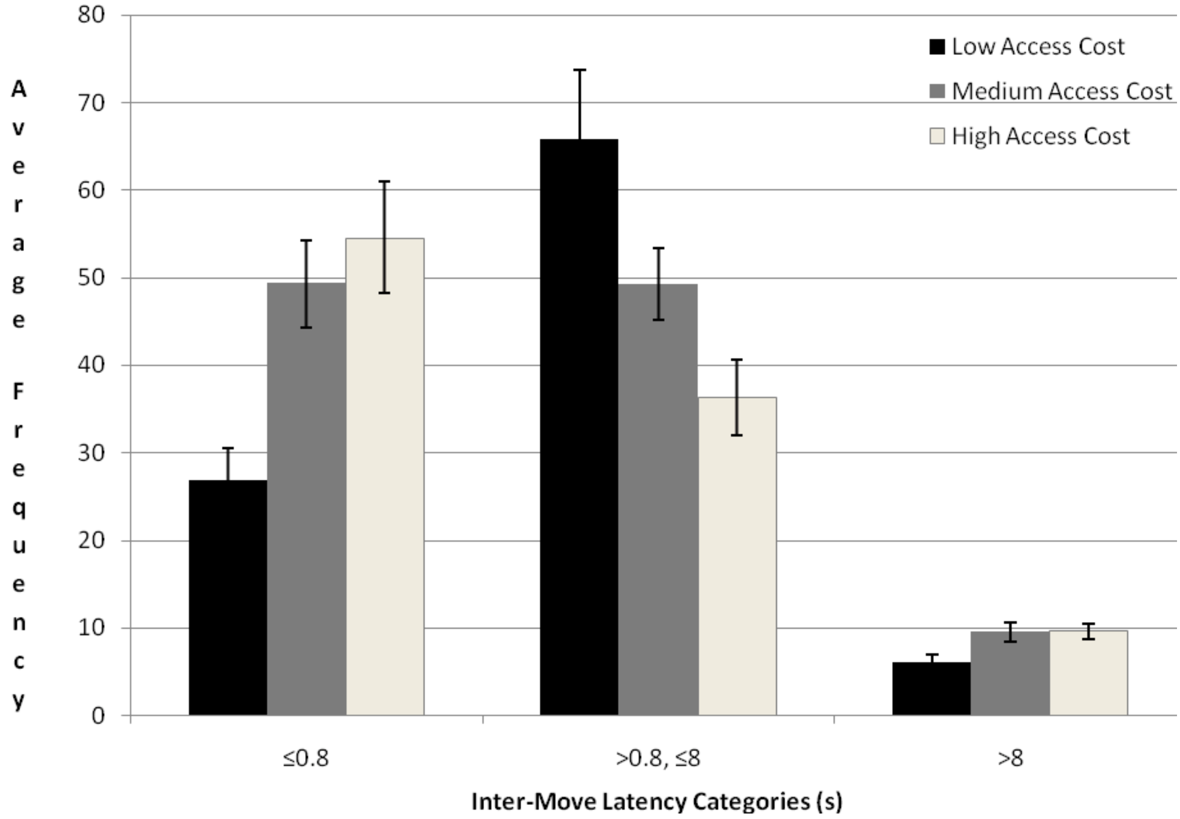

Average Frequency
35
30
25
20
15
10
5
0
Low Access Cost
Medium Access Cost
High Access Cost
≤0.8
>0.8, ≤8
>8
Inter-Move Latency Categories (s)

Figure 3


80
70
60
50
40
30
20
10
0
Average Frequency
Low Access Cost
Medium Access Cost
High Access Cost
≤0.8
>0.8, ≤8
>8
Inter-Move Latency Categories (s)